Industrial Learning Curves: Series Production of the LHC Main Superconducting Dipole

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Questions that we would like to answer:

Is the time necessary to produce 1 unit decreasing with the cumulated production?
How does the learning rate compares with other industries ?

Are there different phases with different drivers in the learning process?

Which is the cost progress ?

Which is the inherent efficiency limit ?

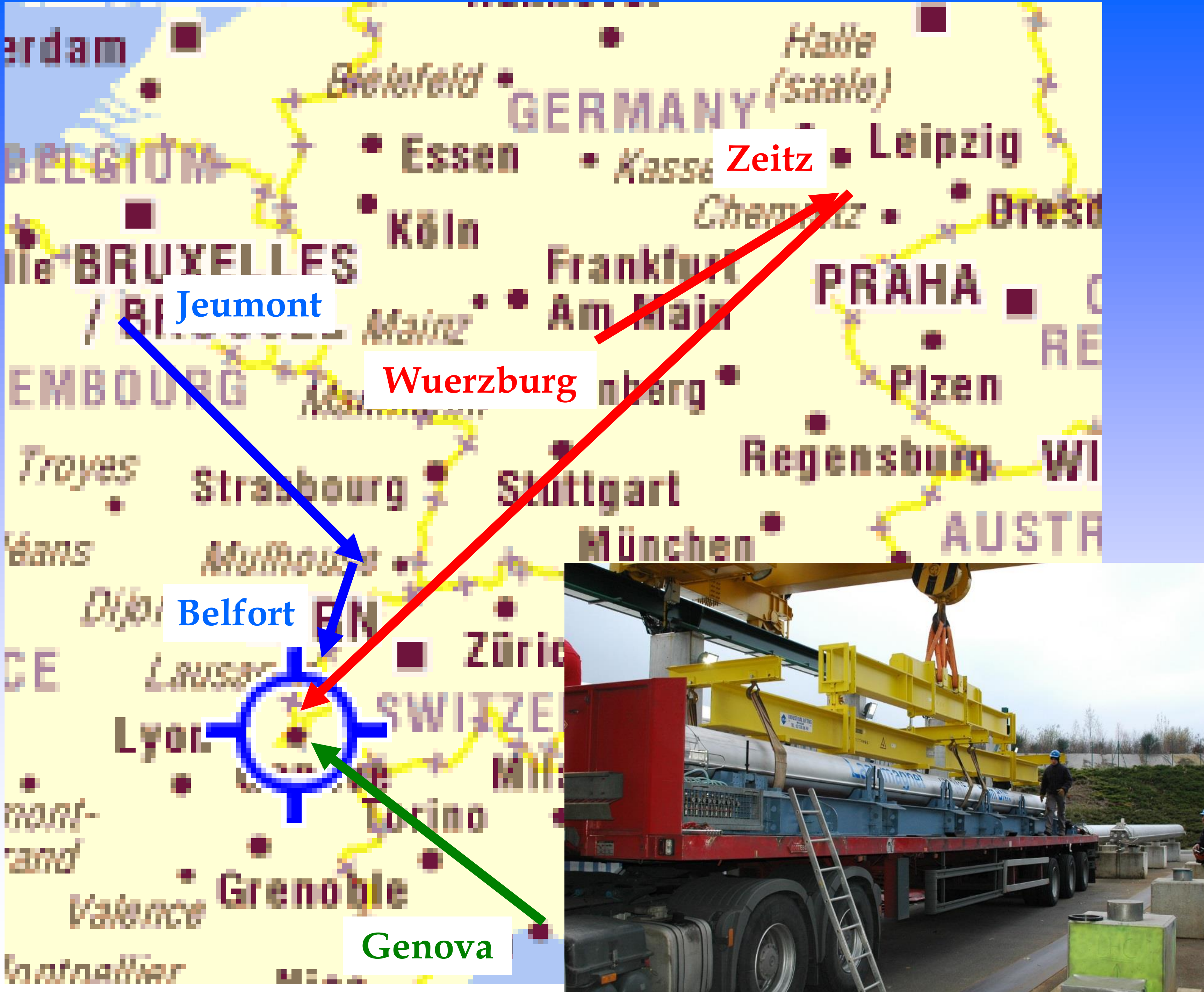
1248 units (1232+16 spare)

CERN

416 units → Ansaldo Superconduttori

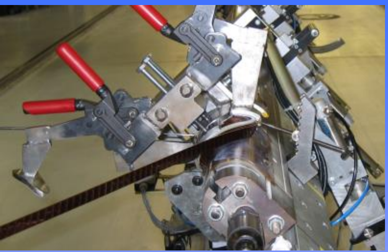
416 units → Babcock Noell Nuclear

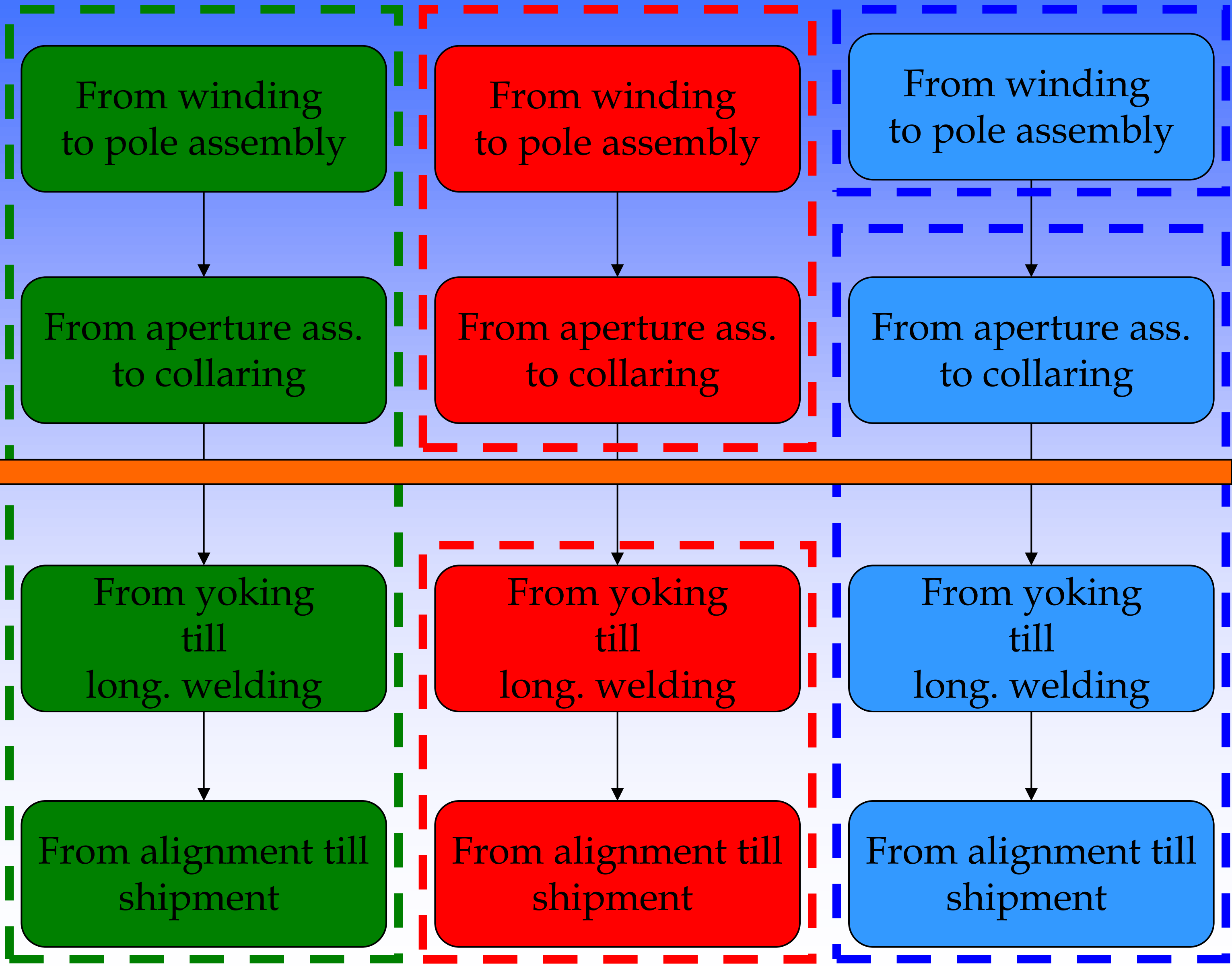
416 units → Consortium Alstom-Jeumont



Zeitz
Wuerzburg
Jeumont
Belfort
Genova
GERMANY
Bielefeld
Essen
Leipzig
Köln
Frankfurt
Am Main
PRAHA
Mainz
Plzen
Troyes
Strasbourg
Stuttgart
Regensburg
München
Mulhouse
Lyon
Grenoble
Valence
Torino

Production organization in the 3 firms



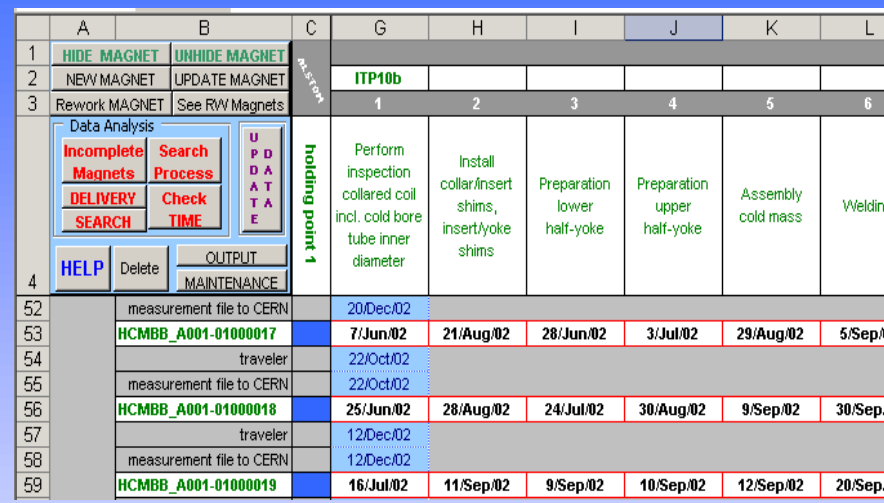


Data needed for the analysis

Time spent in each assembly phase for each magnet

From production follow up macro

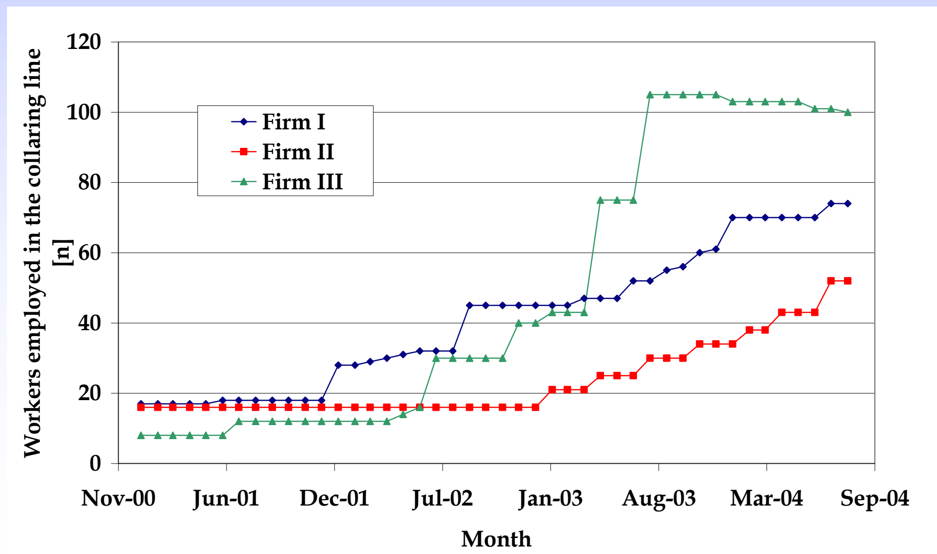
From the Manufacturing and Test Folder (MTF)



	A	B	C	G	H	I	J	K	L
1	HIDE MAGNET	UNHIDE MAGNET							
2	NEW MAGNET	UPDATE MAGNET		ITP10b					
3	Rework MAGNET	See RW Magnets		1	2	3	4	5	6
4	Data Analysis: Incomplete Magnets, Search Process, DELIVERY SEARCH, Check TIME, UPDATE DATA, HELP, Delete	OUTPUT, MAINTENANCE	holding point 1	Perform inspection collared coil incl. cold bore tube inner diameter	Install collar/insert shims, insert/yoke shims	Preparation lower half-yoke	Preparation upper half-yoke	Assembly cold mass	Weldin
52		measurement file to CERN		20/Dec/02					
53		HCMBB_A001-01000017		7/Jun/02	21/Aug/02	28/Jun/02	3/Jul/02	29/Aug/02	5/Sep/
54		traveler		22/Oct/02					
55		measurement file to CERN		22/Oct/02					
56		HCMBB_A001-01000018		25/Jun/02	28/Aug/02	24/Jul/02	30/Aug/02	9/Sep/02	30/Sep
57		traveler		12/Dec/02					
58		measurement file to CERN		12/Dec/02					
59		HCMBB_A001-01000019		16/Jul/02	11/Sep/02	9/Sep/02	10/Sep/02	12/Sep/02	20/Sep

Workforce employed in each production stage

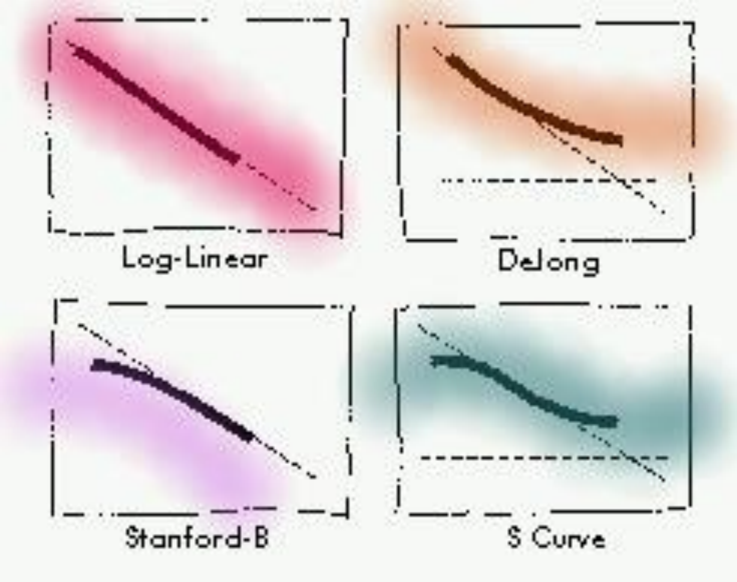
Kindly provided by the 3 CMAs



Data manually cleaned of possible triple time counting for NCRs

4 models to study effect of learning on production time

- Log-Linear: $t_n = t_1 n^b$
- Stanford-B: $t_n = t_1 (n + c_{ex})^b$
- De Jong: $t_n = c_{in} + t_1 n^b$
- S-Curve: $t_n = c_{in} + t_1 (n + c_{ex})^b$



$b<1$

c_{ex} :previous experience

c_{in} :incompressible time (tool limit)

Workers learn to perform tasks faster

Workers learn to perform tasks with fewer errors

Redeployment of workers

New or improved automation and tooling

Optimization of procedures

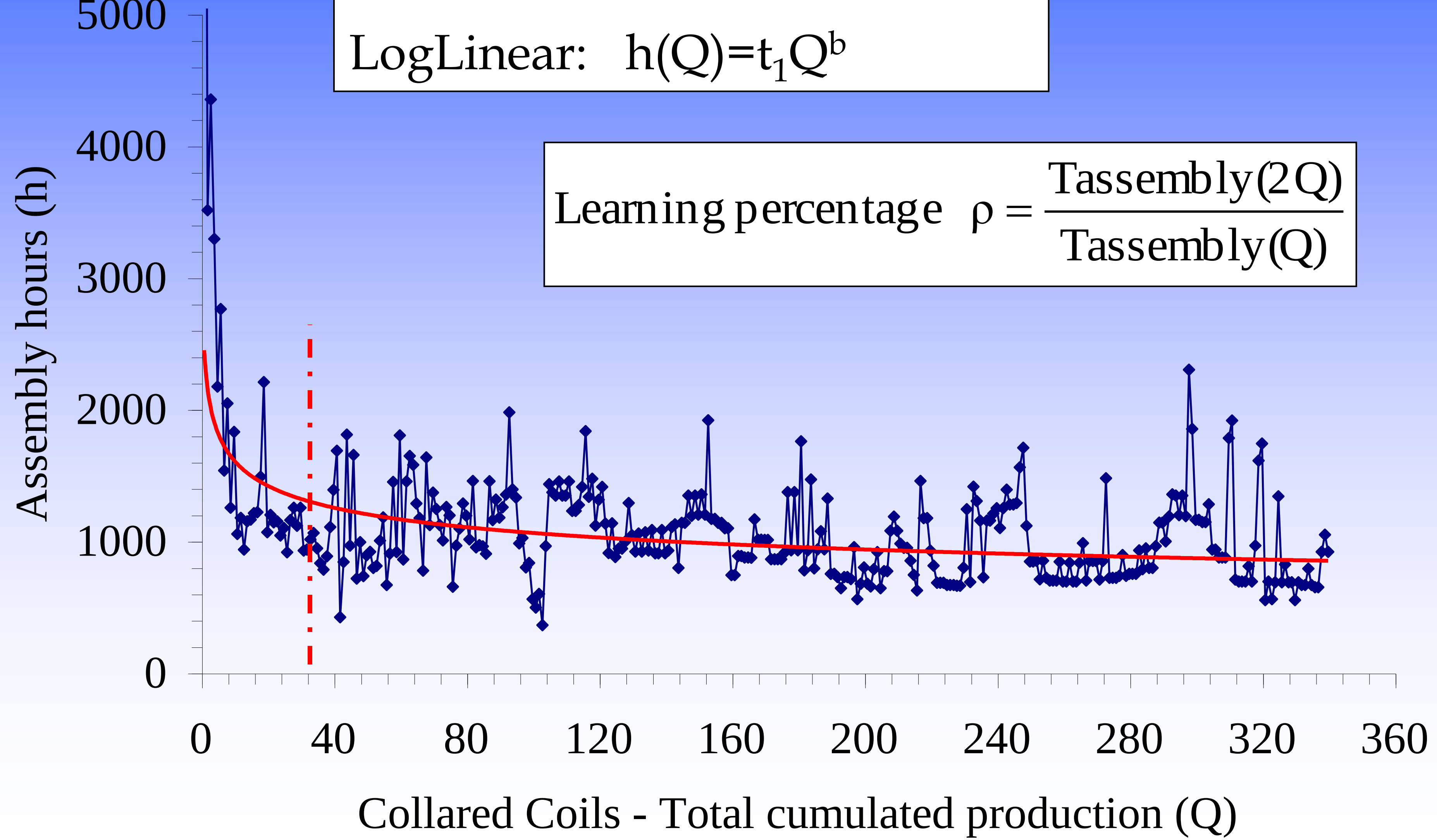
Learning
(reduction in assembly time)

Learning: reducing unit production time

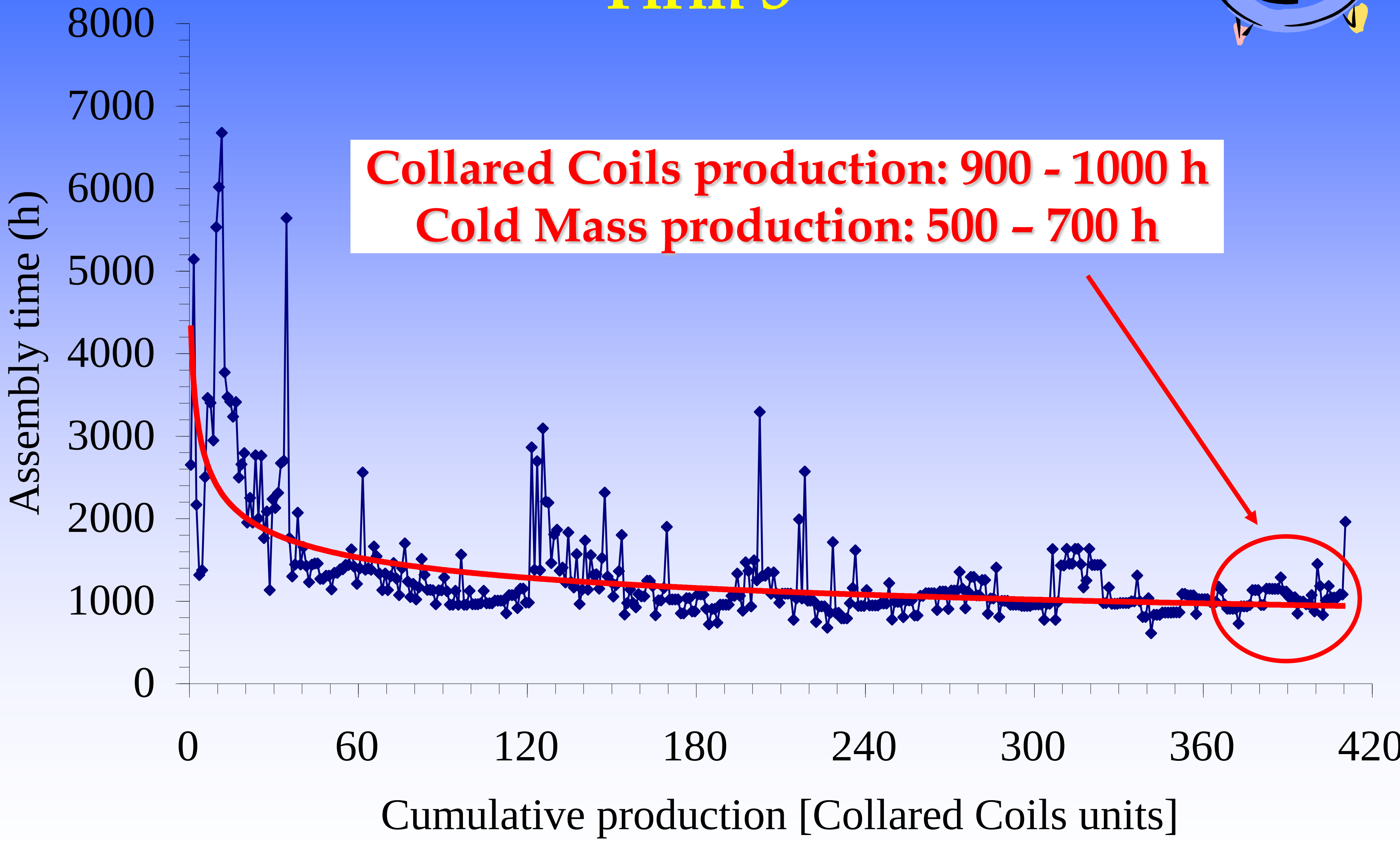
Model to fit production hours:

LogLinear: $h(Q)=t_1 Q^b$

$$\text{Learning percentage} \quad \rho = \frac{\text{Tassembly}(2Q)}{\text{Tassembly}(Q)}$$



Application of Log Linear model: Firm 3



Production hours
Learning percentage of CC & CM

	Firm 1	Firm 2	Firm 3
Collared Coils	81%	88%	83%
Cold Masses	82%	80%	82%

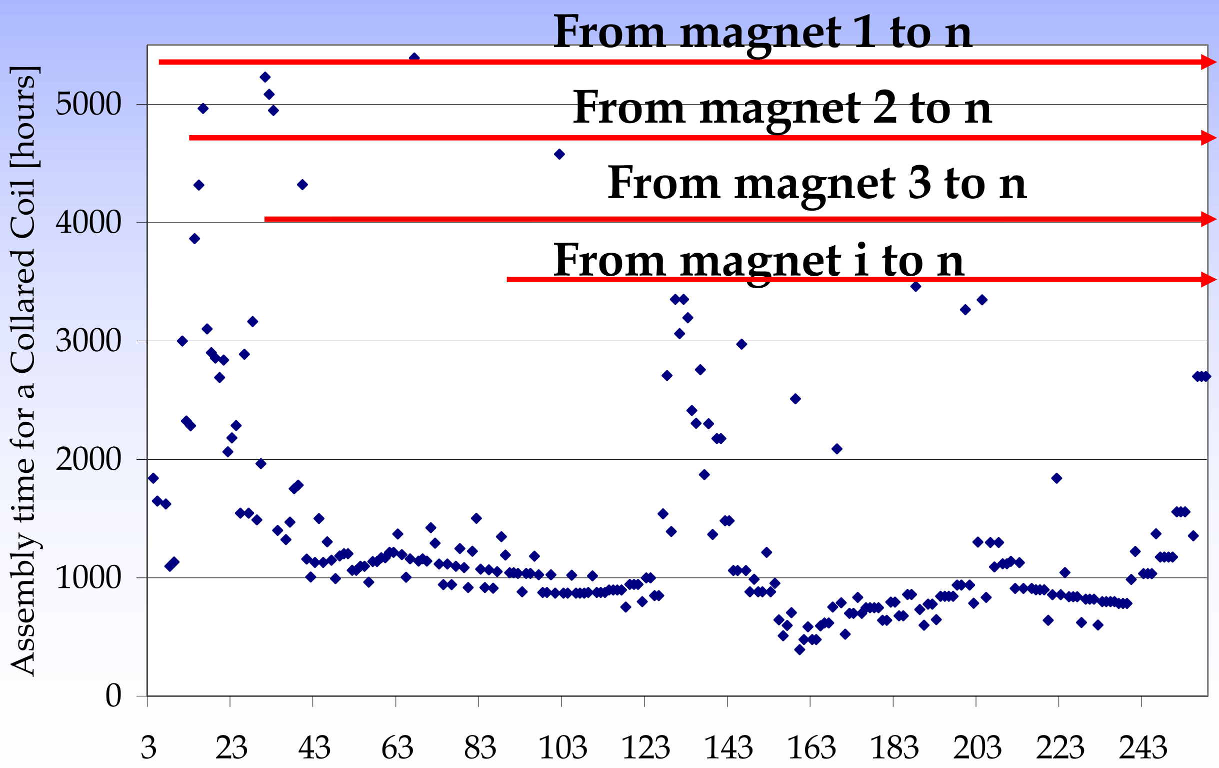
- ρ of the three firms are very close to each other: long term effect of the “Best Practice Sharing Practice”

Comparison with other industries

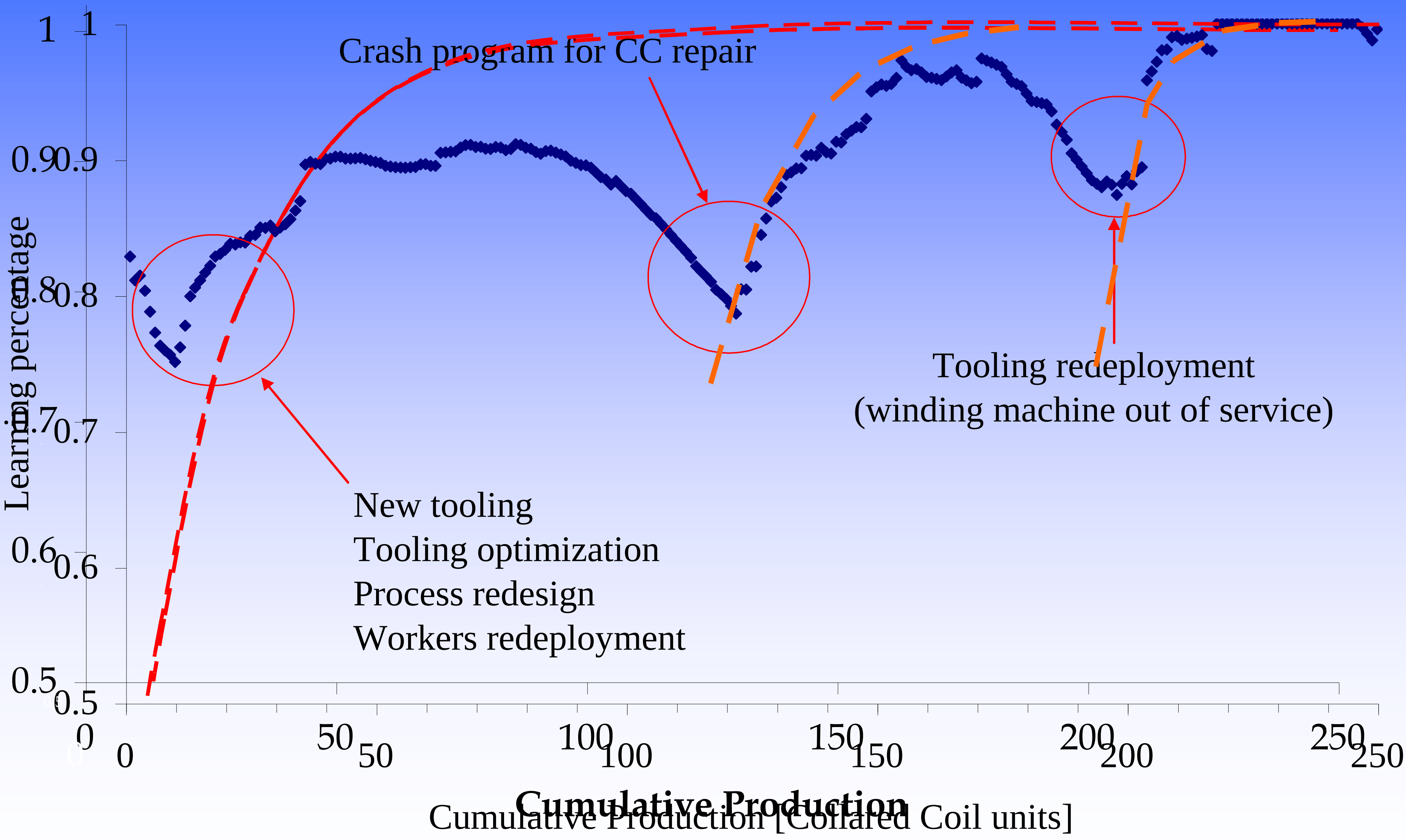
Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
LHC main dipoles	**80%-85%**
Shipbuilding	80%-85%
RHIC magnets	**85%**
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

Process improvement or workers' learning ?

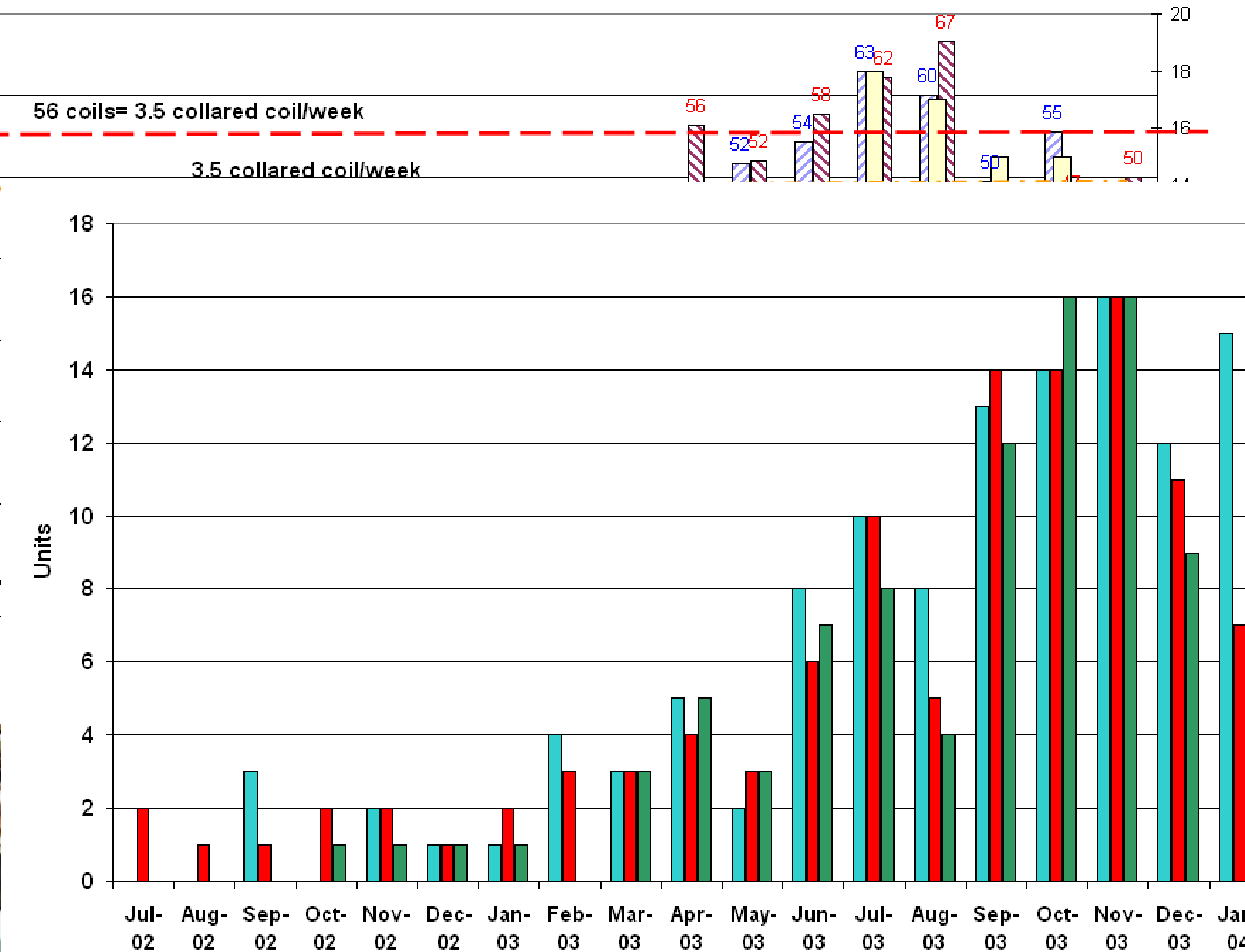
In order to determine if the learning process is a **smooth** process we can try to look at the evolution of the learning percentage along different subset of the production. Differences between phases dominated by the **process redesign** or by the **worker's learning** could be put in evidence



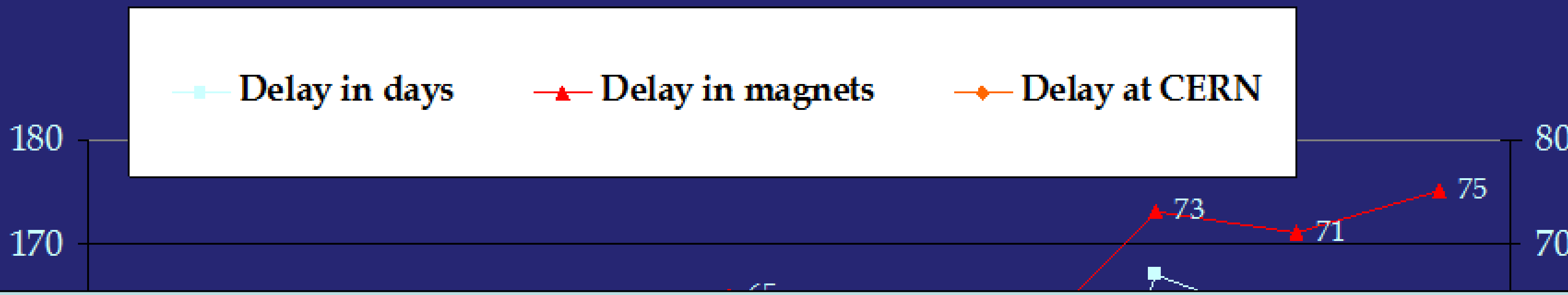
Different drivers on Learning phas



High production rate means a lot of intermediate sub-assembly along the fabrication line



Quality feed back time loop



FCC HORIZON

4500 dipoles
5 years of productions
4 companies
Assembly time 3 months
Necessary production rate: 5 magnets/week
Detection time of quality problem after delivery:
+ 4weeks
Magnets in the assembly line and in store that could need refurbishment

85 units

(if problem related to centrally delivered component 340 units)

Workers learn to perform tasks faster

Workers learn to perform tasks with fewer errors

Redeployment of workers

New or improved automation and tooling

Optimization of procedures

Cost progress or Learning

New and cheaper suppliers

Quantity discounts

Variation of recurring fixed costs

Improvement of logistics

Costs classification

Costs	**Fixed**	**Variable**
Non-recurring	*Overheads* *Tooling*	
Recurring	*Facilities*	*Work* *Materials* *Transport* *Insurance*

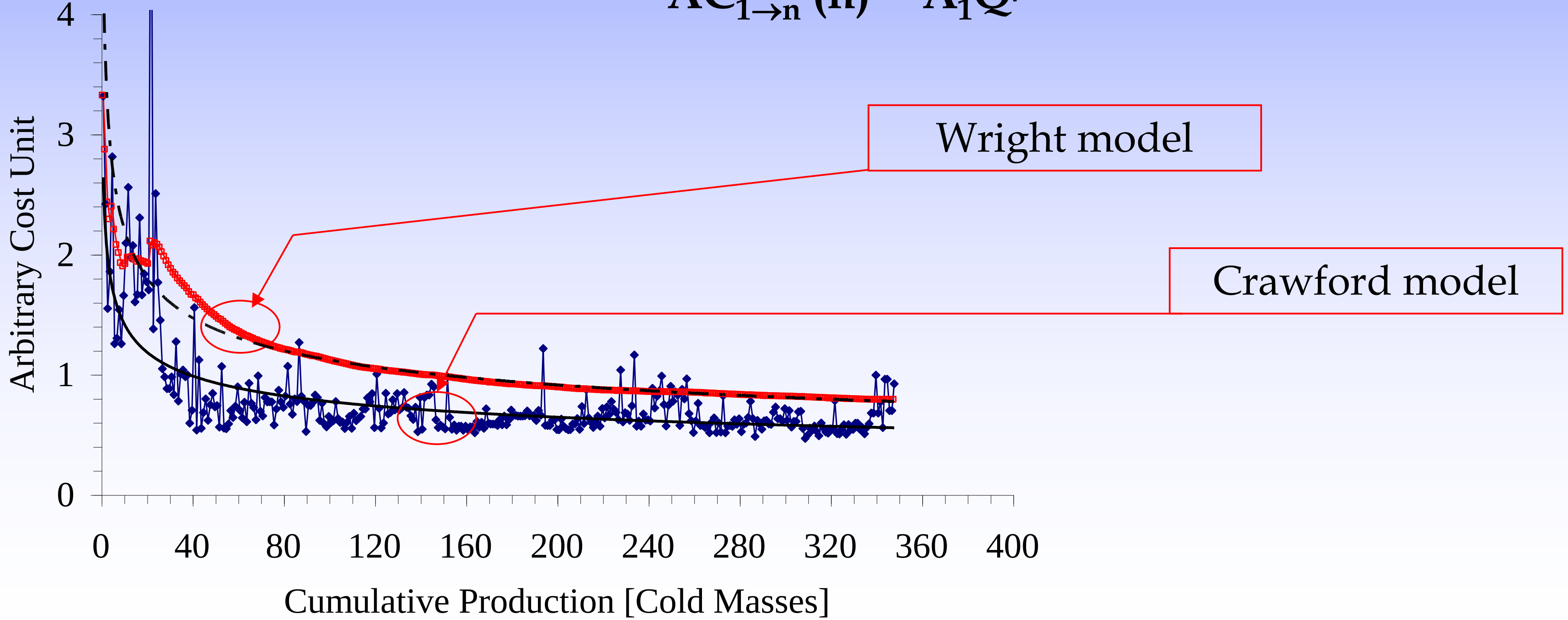
Cost models: Crawford and Wright

- **Crawford: the marginal cost of the unit *Q* is expressed as a power function of the produced quantity:**

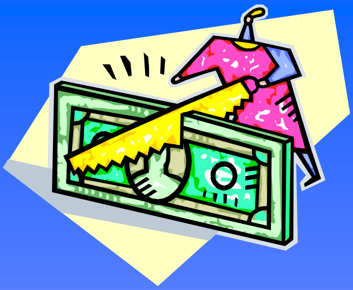
$$MC(Q) = T_1 Qb$$

- **Wright: cumulative average cost of the 1st *Q* units is expressed as power function of the produced quantity:**

$$AC_{1\rightarrow n}(n) = A_1 Q^{\beta}$$



Cost analysis

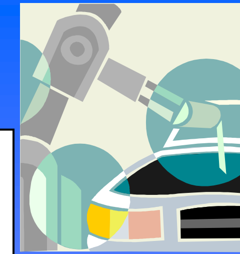


The cost of the units produced has been normalized to the same arbitrary value for the three firms.

Collared Coil production			
Firm	Crawford model	Wright model	Cost 300^{th} unit [A.C.U]
Firm 1	88%	88%	1
Firm 2	90%	86%	0.8
Firm 3	89%	88%	0.8

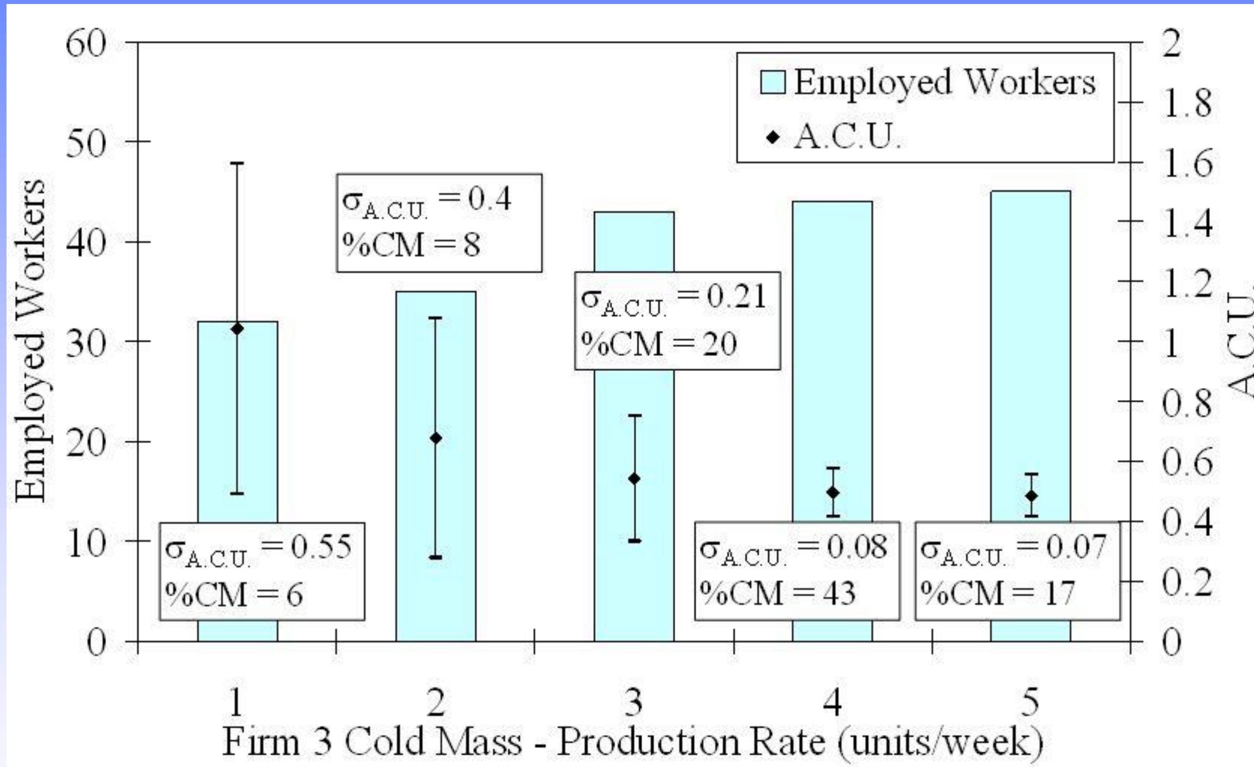
Cold Mass production			
Firm	Crawford model	Wright model	Cost 300^{th} unit [A.C.U]
Firm 1	83%	81%	0.55
Firm 2	82%	81%	0.4
Firm 3	88%	82%	0.4

Limit in production efficiency



- Is the process scalable: higher production rate leads to lower costs?
- Is the tooling a factor limiting the improvement of production?

- The cost corresponding to a production rate must be represented as a statistical distribution
- The production phases are scalable at least to 4-5 CM delivered/week
- The tooling limits the production rate at 5-6 units/week



Conclusions

- The LHC production had an high learning percentage …
- … comparable to industries with the highest learning rates
- Two phases are visible in the learning process: one driven by process improvement, the other by the day by day learning. Changes in procedures and production tuning strongly affect the learning process.
- The efficiency and the productivity are not limited by the installed tooling
- Due to the complexity of NCR detection the risks of large number of magnet rejection should be mitigated with very detailed QC, rapid acceptance screening, and very probably large design margins

FCC the future learning experience